2D Micro Scanner Actuated by Sol-gel Derived Double Layered PZT

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ABSTRACT

2D micro scanners actuated by sol-gel derived double layered PZT actuators were designed and fabricated. In our previous work, the better scanning capability of double layered PZT structures has been investigated [8]. The purpose of this paper is to determine 1D and 2D scanning characteristics of 2D micro scanners with respect to resonant actuations. While resonating with 7.5 V at 3750 Hz and 5350 Hz, the scanning angle of 26±2 degrees and 24±2 degrees were obtained. Furthermore, the new fabrication process greatly improved the residual stress of suspended structures due to the compensation effect of double layered PZT. Wet etching process for PZT not only amended the uniformity, but also increased the device yield economically.

INTRODUCTION

In recent years, there have been considerable researches focused on micro scanners and optical switches using micromachined mirrors. Most of the 1D and 2D micro scanners are reported in connection with a great variety of applications ranging from barcode reading to scanning image projection with laser. Different driving methods, such as electromagnetic, electrostatic, electrothermal, and piezoelectric driving, are used to title the micro mirror plate as a key component [1-5]. Most of the micromirrors are electrostatically driven. But, the applied voltage of up to several hundred volts is necessary depending on the mirror size, maximum scanning angle, and the operation frequency. In addition, the slow response of the electrothermal actuated device cannot be satisfying with respect to wider bandwidth applications.

Deposition of thin piezoelectric PZT layers by different thin film technologies has reached an advanced state. Despite of the promising properties, there are only few reports on the use of such layers as actuator components in micro electro mechanical systems (MEMS) [4,6]. Problems for the applications are mainly caused by the necessity of very small dimension of such devices, in contrast to limitations and tolerances of the used micro technologies. To cope with the problem, the structure design and the fabrication process of the device have to be able to compromise, compensate, or even to use such caused constrains, such as deformation by induced strain.

In particular, the residual stress of the multiple PZT layers derived by the sol-gel method is difficult to control and cannot apply for the cantilever structures due to the serious deformation.

In this paper, 2D micro scanners driven by the double layered PZT (DPZT) actuators were designed and fabricated in order to yield the larger bending force with low actuation voltage and high working frequency. Furthermore, by the use of thermal treatment process and the addition of the platinum film, the residual stress of DPZT structures can be decreased successfully without extra deposition of low stress Si_3N_4 or SiO_2 films. It is beneficial to be used for the cantilever structures, like micro scanners and pressure sensors, and leads to the increase of product yield.

ACTUATION PRINCIPLE

Figure 1 shows the actuation principle of a DPZT actuator with the multi-layered structure, composed of three Pt/Ti films, two PZT layers, and the bottom SiO_2 film. Three Pt films are defined as the upper, center, and bottom electrodes. While applying positive bias voltage to the upper and bottom electrodes (see Figure 1(a)), two PZT layers are biased by the opposite electric fields. If two PZT layers are polarized with the same orientation, the contraction and expansion strain will be induced in the upper and bottom PZT layers, respectively. Theoretically, the opposite strain applied to the other side of neutral surface would increase the bending moment yielding in larger deflection. As shown in Figure 1(b), if negative voltage is applied to reverse the electric fields, the DPZT beam can be bent downward.

Figure 2 describes the design of a 2D micro scanner. Connected a mirror plate with four hinges and four DPZT actuators, the 2D micro scanner can be manufactured without changing fabrication process. In Figure 3(a) and (b), two actuation modes were simulated by the FEM software (ANSYS_5.5). If driving two actuators (beam A and C) at the first resonance frequency, the micromirror would rotate around the x-axis. Similarly, the micromirror would rotate around the y-axis with driving the other two actuators (beam B and beam D) at the second resonance frequency. If mode 1 and mode 2 are excited at the same time, the micromirror can work as 2D scanning motion.
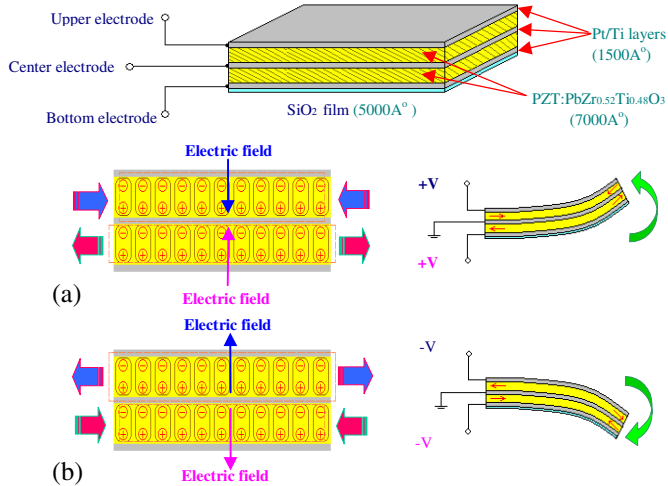
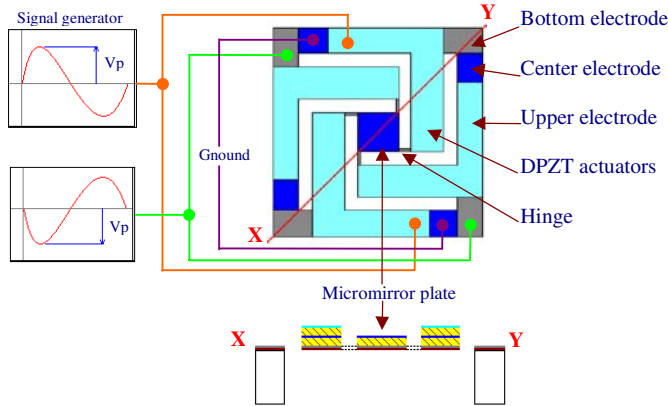Fig. 1. The structure and actuation principle of a DPZT actuator.

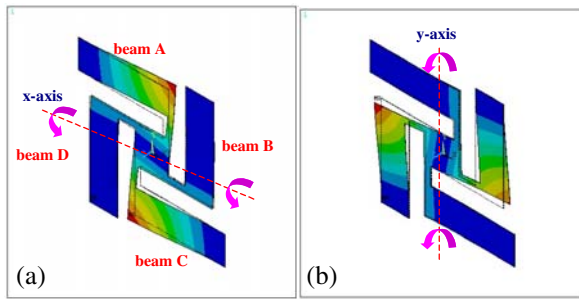Fig. 2. Top-view and cross-section drawings of a 2D micro scanner.

Fig. 3. Two resonating actuations, named (a) mode 1 and (b) mode 2, were simulated by the FEM frequency analysis.

FABRICATION PROCESS

The fabrication process of 2D micro scanners is illustrated in Figure 4. First, the 500 nm-thick thermal SiO_2 film was deposited on both sides of the double-polished silicon substrate. Second, the 50 nm-thick titanium film and the 200 nm-thick platinum film (Pt/Ti layer) were sputtered as the bottom electrode. Further, the PZT layer with a thickness of 700 nm was fabricated

by sol-gel method. After thermal treatment of PZT layers, the second Pt/Ti layer was deposited as the center electrode. Then, the second PZT layer with the thickness of 700 nm was fabricated followed by the formation of the third Pt/Ti layer, as shown in Figure 4(a).

After polarization process of two PZT layers, in Figure 4(b), the upper Pt/Ti layer was patterned by mask 1 and etched by ECR dry etching to define four DPZT beams and upper electrode pads. By the use of diluted HF and Nitric Acid (HF:HNO$_3$:H$_2$O=1:4:8), the underlying PZT layer was removed in very short time, as in Figure 4(c). It is worth to be mentioned that the wet etching acts as a lift-off process and it is useful to get rid of the residual Pt and other particles. As shown in Figure 4(d) and 4(e), followed by the same steps, the center and bottom Pt/Ti layers were respectively patterned by Mask 2 and Mask 3 to define the mirror plate, the center and bottom electrode pads, and four orthogonally rotational hinges. After etching the frontside and backside of thermal SiO_2 films, the ICP dry etching was used to release the complete cantilever structures, as indicated in Figure 4(f). Furthermore, the CO_2 supercritical point drying method was used to prevent the sample from surface tension.

(a) Deposit three Pt/Ti layers and two PZT layers

(b) Etch the upper Pt/Ti

(c) Remove the upper PZT

(d) Etch the center Pt/Ti and the bottom PZT

(e) Etch the bottom Pt/Ti and SiO$_2$
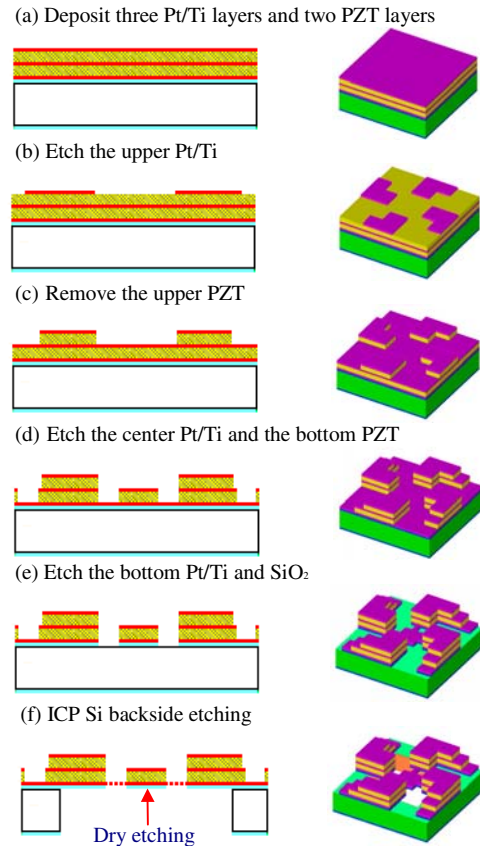
(f) ICP Si backside etching

Dry etching

Fig. 4. The fabrication process of 2D micro scanners.

Figure 5(a) shows the SEM image of the fabricated 2D micro scanner. The chip dimension is 3x3 mm^2 with the thickness of 400 μm. The size of the released mirror plate is 300x300 μm^2 and the size of four DPZT beams is 800x230 μm^2. After bonding process, micro scanners with different chip size were packaged in 14 pin DIP

packages, as shown in Figure 5(b). The upper one is the packaged micro scanner with the chip size of 3x3 mm^2; the bottom one shows the packaged micro scanner with the chip size of 1x1 mm^2.
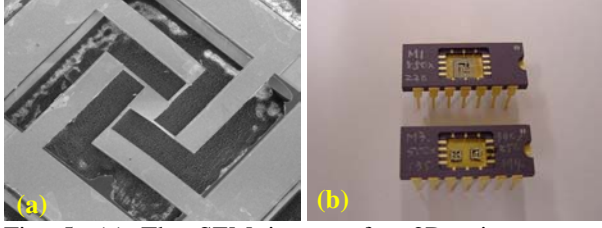

Fig. 5. (a) The SEM image of a 2D micro scanner supported by four DPZT beams; (b) The final chips packaged in the 14 pin DIP package.

EXPERIMENT

In Figure 6, the laser interferometer and the FFT-analyzer are set up to measure the resonance frequency of 2D micro scanners. Under the microscope, the He-Ne laser is focused on the center of the micromirror plate attached on a sub mount. The laser point is reflected to the origin point of a screen. While resonating the micro scanner, the laser point moves and a scanning line can be obtained. The scanning angle of 2D micro scanners can be calculated by the equations as

$$\text{Scanning angle} \quad \theta = 2 \cdot \tan^{-1} \left[\frac{\left(\frac{D_s}{2} \right)}{L} \right]$$

, where D_s is the scanning length of the laser point. L is the horizontal distance between micro scanners and the screen.
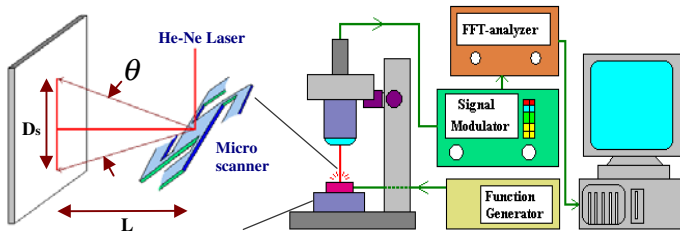

Fig. 6. Set up for scanning angle measurement.

As Figure 7 shows, the resonance frequencies of a 2D micro scanner with respect to the analogic signal Vr measured at 3750 Hz (1st), 5350 Hz (2nd), 7475 Hz (3rd), and 15680 Hz (4th) respectively. Figure 8 illustrated the frequency response of a 2D micro scanner actuated with the amplitude of 7.5V in the form of sine wave. The 4th resonance frequency was ignored because of the low resonance Q value.
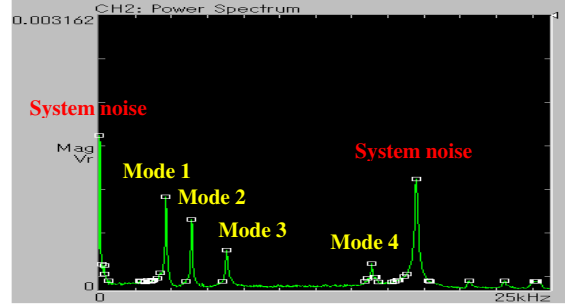

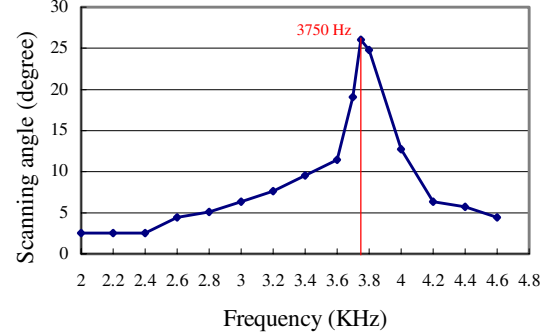Fig. 7. Frequency spectrum of the 2D micro scanner.

Fig. 8. Frequency response of the 2D micro scanner.

While resonating two beams with the amplitude of AC 7.5V (15V$_{p-p}$), the scanning angles of mode 1 and mode 2 were 26±2 degrees and 24±2 degrees. The scanning patterns of mode 1 and mode 2 are almost orthogonal as shown in Figure 9(a) and (b). The pattern of mode 3 has an elliptical or a circular shape respectively, as shown in Figure 9(c). If four beams were driven at mixed vibration with mode 1 and mode 2, a 2D scanning image was obtained as in Figure 9(d).

Furthermore, the relation between applied voltage and the scanning angle was measured under one-beam and two-beam actuations respectively, as shown in Figure 10. Resonating one beam with 7.5V at mode 1 (3750 Hz), the scanning angle was 17º, which was the same as that of the two-beam actuation with 3V. Therefore, the scanning angle can be controlled from 4º to 26º. In the same manner, actuating the other two beams at mode 2 leads to a scanning range from 4º to 24º. It means that the rectangular scanning pattern can be controlled from the minimum area of 4ºx4º to the maximum area of 24ºx26º. However, with more than 7.5V, the 1D and 2D scanning patterns became significantly curved and uncontrollable because of the deformation of the mirror plate.

In order to verify the improved residual stress of a DPZT structure, micro scanners actuated by the 700 nm-thick and 1400 nm-thick single layered PZT (SPZT) were fabricated respectively. After releasing the cantilever structures, in the case of the 700 nm-thick SPZT micro scanner, four actuator beams were deflected upward and a deformation of the mirror plate was observed obviously due to residual stress, as shown in Figure 11(a). With the addition of the center Pt/Ti film (see Figure 11(b)), the opposite film stress compensated the residual stress

induced from the sol-gel derived multiple PZT coating process. For the 1400nm-thick SPZT micro scanner, the larger residual stress deflected four actuator beams and broke the hinges connected with the mirror plate.
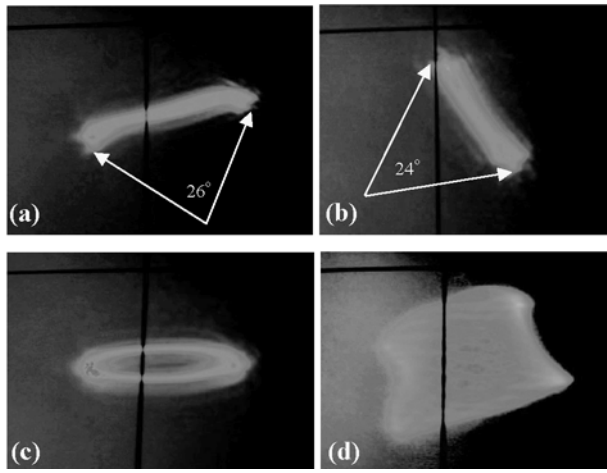

Fig. 9. Scanning patterns actuated at (a) mode 1 (3750 Hz); (b) mode 2 (5350 Hz); (c) mode 3 (7475 Hz); (d) mode 1 and mode 2.
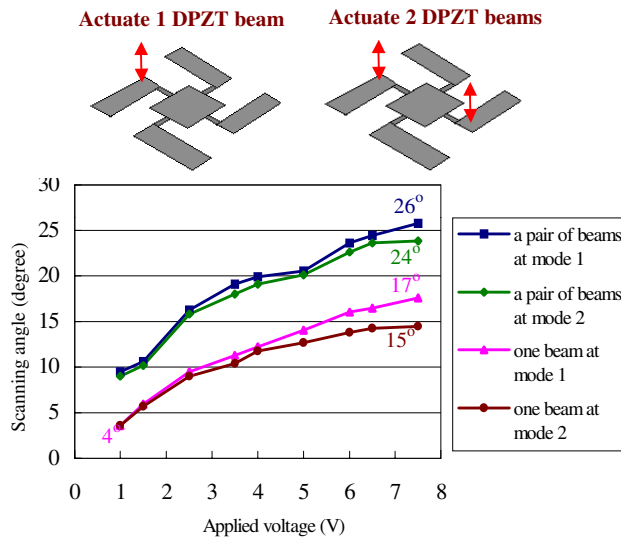

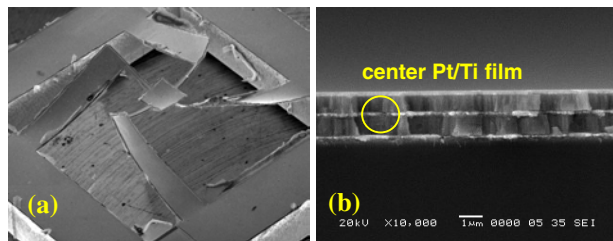Fig. 10. Scanning angle of one-beam and two-beam actuations versus applied voltage.

Fig. 11. The SEM pictures show (a) the 700nm-thick SPZT micro scanner, and (b) the cross-section of a DPZT structure with two 700nm-thick PZT layers.

CONCLUSIONS

This study investigated the effects of the double layered PZT structure on scanning performance and the applications of 2D micro scanners. Under resonant actuation, 1D and 2D scanning capability with respect to applied voltage have been demonstrated.

The low residual stress of the DPZT cantilever device is based on the long time thermal treatment and the stress compensation. The same fabrication process can provide 1D as well as 2D micro scanners. Large scanning and deflection angles resulting from the opposite strain of double PZT layers were achieved with low actuation voltage and high resonance frequency. However, the deformation of the micro mirror plate may cause an uncontrollable scanning motion.

In order to increase the performance of the device, the further theoretical studies and experiments are currently undergoing. The new design with the improved resolution of the silicon base mirror structure is in progress.

ACKNOWLEDGMENTS

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